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Microcontroller-based interface circuit for inductive sensors

Zivko Kokolanski[a], Josep Jordana[b], Manel Gasulla[b], Vladimir Dimcev[a], Ferran Reverter[b,]*

[a]*Ss. Cyril and Methodius University, Ruger Boskovic bb, 1000 Skopje, Republic of Macedonia*
[b]*e-CAT Group, Universitat Politècnica de Catalunya-BarcelonaTech, C/ Esteve Terradas 7, 08860 Castelldefels (Barcelona), Spain*

Abstract

This work proposes a fully-digital interface circuit for the measurement of inductive sensors using a low-cost microcontroller (μC) and without any intermediate active circuit. Apart from the μC and the sensor, the circuit just requires an external resistor and a reference inductance so that two RL circuits with a high-pass filter (HPF) topology are formed. The μC appropriately excites such RL circuits in order to measure the discharging time of the voltage across each inductance (i.e. sensing and reference) and then it uses such discharging times to estimate the sensor inductance. Experimental tests using a commercial μC show a non-linearity error (NLE) lower than 0.5 %FSS (Full-Scale Span) when measuring inductances from 1 mH to 10 mH, and from 10 mH to 100 mH.

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Keywords: Inductive sensor; microcontroller; sensor electronic interface.

1. Introduction

Inductive sensors are widely used in industry to measure displacement or distance of metallic objects, and other physical quantities (e.g. pressure [1]) that indirectly cause a displacement. Interface circuits for those sensors generally rely on either a relaxation oscillator providing a time-modulated signal [1] or an AC-excited bridge providing an amplitude-modulated signal [2]. In both cases, however, several active electronic circuits (e.g. comparators, timers, operational amplifiers and/or an analog-to-digital converter) are required between the sensor and the processing μC. With the aim of reducing the cost and power consumption of electronic interfaces, the

* Corresponding author. Tel.: +34 934137076; fax: +34 934137007.
E-mail address: ferran.reverter@upc.edu

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concept of "direct interface circuit", where the sensor is directly connected to a μC without any intermediate circuit, has been widely proposed, analyzed and tested for resistive [3,4] and capacitive [5,6] sensors, but not for inductive sensors. A circuit for the direct measurement of inductive sensors was suggested in [7,8], but it was not either analyzed or tested; moreover, the effects of the parasitic output resistance of the port pins of the μC in that circuit are quite critical [7]. For this reason, this work proposes and experimentally analyses a novel direct interface circuit for inductive sensors with a topology different than that suggested in [7,8]. The proposed circuit is mainly intended for inductive sensors based on a change of either the magnetic reluctance [1] or the number of turns of the coil winding that operate at low-medium frequencies and whose nominal inductance is some units or tens of milihenry [1,2]. For other types of inductive sensors (such as eddy-current sensors that operate at high frequencies [9,10]) or for values of inductance lower than 1 mH, the proposed circuit could have significant limitations.

2. Operating principle

The proposed direct interface circuit for inductive sensors is shown in Fig. 1a. Apart from the μC and the sensor (L_x), this electronic interface just needs a reference inductance (L_{ref}) that is used for a one-point calibration, and an external resistor (R_{ext}) that limits the current provided by the μC. In such an electronic interface, two RL circuits with a HPF topology are formed: R_{ext} together with L_x, and R_{ext} together with L_{ref}. Each RL circuit is appropriately excited by the μC so as to measure (through an embedded digital timer) the discharging time (T_x and T_{ref}) of the voltage across each inductance (L_x and L_{ref}, respectively) and then estimate L_x as $(T_x/T_{ref})\cdot L_{ref}$. In comparison with the circuit suggested in [7,8] that relies on a low-pass filter (LPF) topology, the proposed circuit based on a HPF topology provides a longer time constant (and, hence, a longer discharging time) since the required R_{ext} can be smaller. Note that the HPF topology intentionally uses the parasitic output resistance of the digital port that controls the charging-discharging process (i.e. Pin 1 in Fig. 1a) to define, together with R_{ext}, the equivalent resistance of the RL circuit.

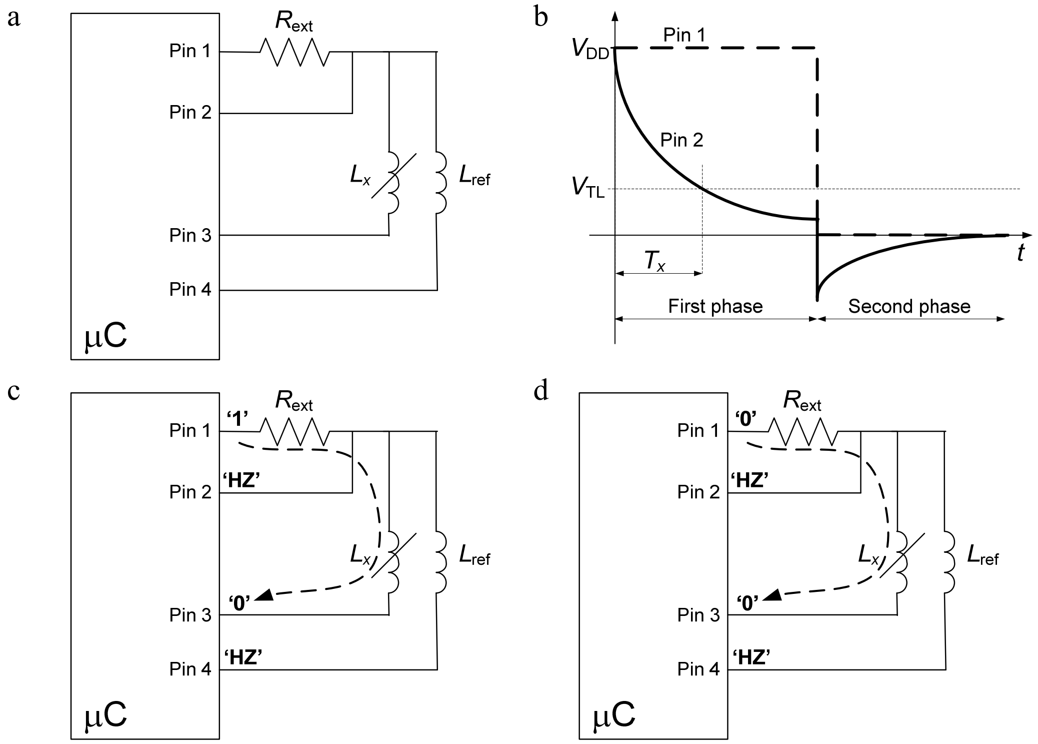

Fig. 1. (a) Microcontroller-based interface circuit for an inductive sensor (L_x). (b) Transient response of the voltage at pins 1 and 2 when measuring the RL circuit that includes L_x. (c) First phase for the measurement of L_x. (d) Second phase for the measurement of L_x.

The measurement of the discharging time of each RL circuit requires two phases. Figs. 1c and 1d show, respectively, the state of the port pins of the µC during the first and second phase when measuring the RL circuit that includes L_x. In the first phase (Fig. 1c), pin 1 generates a step pulse (i.e. from a digital ‘0’ to ‘1’, or from 0 V to the supply voltage, V_{DD}), pin 3 provides a digital ‘0’ (i.e. 0 V), and pins 2 and 4 are in a high-impedance (HZ) state. This configuration results in a discharging voltage across L_x, as shown in Fig. 1b, that is monitored by pin 2. When such a discharging voltage reaches the “digital” threshold voltage (V_{TL}) of pin 2, then the embedded timer stops and a digital number (T_x) with information about the length of the discharging time is registered. In the second phase (Fig. 1d), pin 1 provides a digital ‘0’, whereas the other pins do not change their state. With this configuration, the inductor current is discharged towards zero. This phase must be long enough (at least five times the discharging time constant) so as to be sure that the energy stored before in the inductance is removed. Afterwards, the circuit operates similarly for the measurement of the RL circuit that includes L_{ref}, but pin 3 is in HZ state and pin 4 provides a digital ‘0’, and the result is the digital number T_{ref}.

3. Experimental results

The direct interface circuit shown in Fig. 1a has been implemented using a PIC16F877 (Microchip) µC running on a 20-MHz oscillator and with a supply voltage of V_{DD} = 5 V. This is a common 8-bit CMOS µC that has a port (PortB) with digital inputs/outputs to carry out the operating principle explained before and a 16-bit embedded timer (Timer1). Within the PortB, pin RB0 (which includes a Schmitt Trigger buffer) was in charge to perform the function of pin 2 in Fig. 1a; that pin was set to interrupt the CPU of the µC when a falling edge of the input signal (i.e. the discharging voltage shown in Fig. 1b) was detected. The measurements carried out by the µC were sent to a personal computer through a serial RS232 interface. To eliminate potential noise/interference affecting the measurements, the serial logic level translator MAX232 was supplied by an independent voltage regulator.

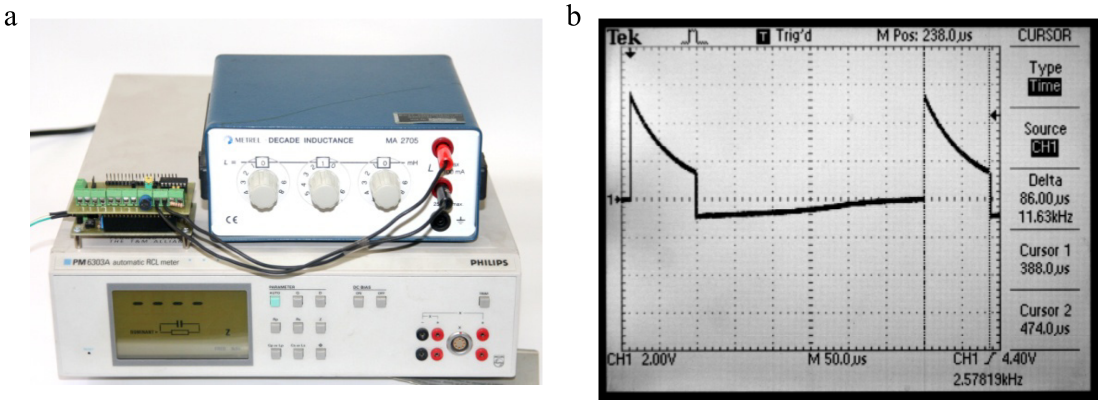

Fig. 2. (a) Measurement set-up employed to test the interface circuit in Fig. 1a. (b) Experimental transient response of the voltage at pin 2.

Fig. 2a shows the measurement set-up employed to test the proposed direct interface circuit. The inductance values corresponding to L_x (between 1 mH and 100 mH) were provided by a variable decade inductance box (Metrel MA 2705) and the actual value of those inductances was measured by an RCL meter (Philips PM6303A) with a relative uncertainty of 0.25 %. The reference inductance was L_{ref} = 1 mH; note that higher values of L_{ref} (e.g. 10 mH or 50 mH) would result in a bulky and expensive component. The external resistor was R_{ext} = 100 Ω that is the minimum value that can be used to limit the current to 25 mA (which is the maximum current that can be sourced by a port pin) taking into account the parasitic output resistance of the port pins of the µC, which is about 100 Ω for a pair of pins providing a digital ‘1’ and a ‘0’. Using these components, the transient response of the voltage at pin 2 was acquired by a digital oscilloscope, as shown in Fig. 2b. In comparison with the theoretical transient response represented in Fig. 1b, there is a significant difference at the beginning of the second phase. This is because the ESD protection diode embedded into pin 2 becomes forward biased and then the voltage is limited to around –0.7 V.

Figs. 3a and 3b show, respectively, the experimental results when inductances from 1 mH to 10 mH, and from 10 mH to 100 mH were measured. These two figures also show the straight line fitted to the experimental data by means of the least-squares method and the NLE expressed as a percentage of the FSS. According to Figs. 3a and 3b, the maximum NLE is, respectively, 0.36 %FSS and 0.42 %FSS, which are remarkable values considering the simplicity of the proposed circuit. The cause of this non-linearity needs to be further investigated but it could be due to: (i) the quantization involved in the time-to-digital conversion, (ii) the mismatch of the parasitic resistances of L_x and L_{ref}, and/or (iii) the mismatch of the parasitic output resistances of the port pins of the µC.

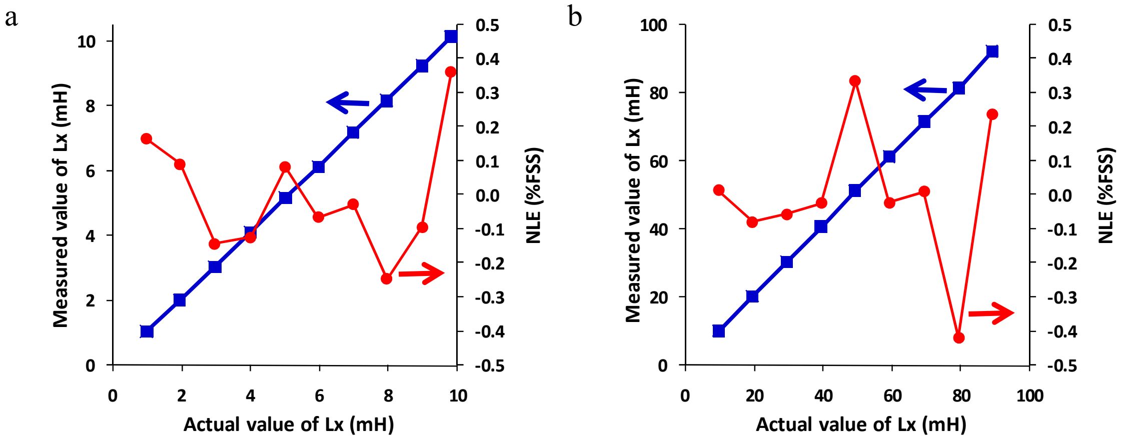

Fig. 3. Experimental results of the circuit in Fig. 1a when measuring inductances (a) from 1 mH to 10 mH, and (b) from 10 mH to 100 mH.

4. Conclusions

This work has gone a step further in the field of direct interface circuits by proposing and testing a circuit for inductive sensors. The proposed circuit uses a low-cost µC to measure the discharging time of two RL circuits formed by the sensor inductance, a reference inductance and an external resistor. The sensor inductance is then estimated by applying a single-point calibration that uses such discharging times. The measurement of inductances in the range of units and tens of milihenry has shown a NLE lower than 0.5 %FSS, which is a remarkable value considering the simplicity of the proposed circuit. In the near future, such a direct interface circuit will be used to measure an inductive displacement sensor, and a complete analysis of the error sources will be done.

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